

CP, CPT and Rare Decays *

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Abstract

We describe possible kaon physics goals to achieve with a high luminosity Φ -factory. We motivate the relevance to improve the present bounds on CPT kaon physics quantities. Also, the interferometer machine Φ -factory is useful to study CP violating/conserving effects in kaon decays. Thus we investigate $K \rightarrow 3\pi$ amplitudes: charge asymmetries are interesting in charged kaon decays. In the case of neutral kaon decays one can study directly $K_S \rightarrow 3\pi$ or interferences effects. Interference may also be used to study the CP even $K_S \rightarrow \pi^+\pi^-\pi^0$ and final state interactions.

INTRODUCTION

Recently the majestic CPT tests [1, 2, 3, 4] in kaon physics have been challenged by neutrino physics [5] where it has been argued that neutrino physics probes a shorter scale than the typical scale probed by kaon physics. I recall, as I will show later, that kaon physics maybe sensitive to Planck scale physics [6, 7]. We take the pragmatic approach that an high luminosity Φ -factory must improve the CPT kaon physics tests to match the neutrino physics level. Bell-Steinberger relations, dictated by the unitarity conditions, are the main tool to improve the CPT kaon physics bounds. Now these bounds are limited by the $K \rightarrow \pi\pi$ measurements, so it is compulsory to improve these experimental results. We will review the CPT neutrino bounds first, then the present bounds in kaon physics from Bell-Steinberger relations. Finally we mention other interesting non-CPT violating physics issues achievable at an high luminosity Φ -factory.

CPT VIOLATION

Relativistic quantum field theories predict a very important property: CPT invariance [8], which holds under the following three hypotheses:

- Lorentz invariance
- Hermiticity of the Hamiltonian
- Locality.

CTP-violation and/or the accuracy on which we test CPT is fundamental in physics and searched in several experiments [9]. A theoretical acceptable framework to generate CPT-violation is the one suggested in Ref. [10],

where departures from Lorentz invariance generate CPT-even and CPT-odd terms: small non-invariant terms are added to the Standard Model Lagrangian, these are assumed renormalizable (dimension ≤ 4), invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y$ and rotationally and translationally invariant in a preferred frame (then fixed to be the one where the cosmic microwave background is isotropic). String theory is presumably valid up to the Planck scale and argued to be CPT-conserving. But spontaneous CPT-violation is still allowed: S-matrix elements may violate CPT according to the details of the low energy limit. In fact string theory can generate Lorentz and CPT violating terms [11]. Actually there are also explicit quantum field theory examples of spontaneous CPT-violation [12]. Just to give an explicit example of Lorentz violation we mention the one particularly used in cosmic rays and neutrino tests. We change the coefficient of the square of the magnetic field in the Lagrangian of quantum electrodynamics:

$$\vec{B}^2 \rightarrow (1 + \epsilon)\vec{B}^2 \quad (1)$$

This will cause the velocity of light c , given by $c^2 = 1 + \epsilon$ to differ from the maximum velocity of particles, which remains equal to one. This is just one of the terms to be added to the Standard Model Lagrangian [10], invoking an explicit violation of Lorentz invariance.

Recently Ref.[13] has challenged CPT by giving up locality but not Lorentz invariance; they add to the usual Dirac term the following non-local fermionic action

$$S = \frac{i\eta}{\pi} \int d^3x \int dt dt' \bar{\psi}(t, \mathbf{x}) \frac{1}{t - t'} \psi(t', \mathbf{x}).$$

In order to prove that a ~~CPT~~ lagrangian can generate physical amplitudes it is important to check causality: however it is still disputed if this model produces a satisfactory CPT-violating model [14].

~~CPT~~ in ν 's and challenge

As we shall see in the kaon sector CPT and quantum mechanics are already tested to an interesting level [1]

$$|m_K - m_{\bar{K}}| < 10^{-18} m_K \implies |m_K^2 - m_{\bar{K}}^2| < 0.5 eV^2. \quad (2)$$

This already probes an interesting size: in fact quantum gravity may generate a CPT violating kaon mass term of order [6]:

$$\frac{m_K^2}{M_P} \quad (3)$$

Murayama [5] has wondered if neutrino can challenge this limit. In fact neutrino sector plays now an important role

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in flavour studies, and new experiments in their attempts to pin down the neutrino flavour matrix, the PMNS matrix analogous to the CKM matrix, will give us also useful information for CP and CPT studies.

Already the present limits on solar neutrino and antineutrino mass difference:

$$|\delta| \equiv |\Delta m_\nu^2 - \Delta m_\nu^2| < 1.3 \times 10^{-3} \text{ eV}^2 \text{ (90\% C.L.)} \quad (4)$$

constitutes an interesting challenge for kaon physics. Though of course, there is no reason *a priori* to expect the same amount of CPT violation in the two systems.

This scale is comparable to the measured dark energy

$$\rho_\Lambda \sim (2 \times 10^{-3} \text{ eV})^4 \quad (5)$$

We remind also that different spectra for neutrinos and antineutrinos has been invoked in order explain LSND data [15].

~~CPT~~ in the K 's mass and width matrix

Though there are arguments [16] suggesting possible quantum mechanics violations and possible tests in interferometry machines like Φ -factories and CPLEAR [17], here we assume that conservation of probability has a stronger validity than CPT, thus we can keep unitarity but relax CPT violation. In the kaon system we can describe mass and decay eigenstates by the diagonalization [2, 4, 18]

$$\begin{pmatrix} M_{11} - i\Gamma_{11}/2 & M_{12} - i\Gamma_{12}/2 \\ M_{21} - i\Gamma_{21}/2 & M_{22} - i\Gamma_{22}/2 \end{pmatrix}$$

$$\text{CPT} \Rightarrow M_{11} = M_{22} \quad \Gamma_{11} = \Gamma_{22},$$

with the eigenvectors

$$K_{S,L} = \frac{[(1 + \epsilon_{S,L}) K^0 + (1 - \epsilon_{S,L}) \bar{K}^0]}{\sqrt{2(1 + |\epsilon_{S,L}|^2)}}$$

Encoding in Δ the CPT violating contributions

$$\Delta = \frac{\frac{1}{2} [M_{11} - M_{22} - \frac{i}{2} (\Gamma_{11} - \Gamma_{22})]}{m_L - m_S + i(\Gamma_S - \Gamma_L)/2} \quad (6)$$

we can write

$$\begin{aligned} \epsilon_{S,L} &= \frac{-i\Im(M_{12}) - \frac{1}{2}\Im(\Gamma_{12})}{m_L - m_S + i(\Gamma_S - \Gamma_L)/2} \mp \Delta \\ &= \epsilon_M \mp \Delta \end{aligned}$$

$$\epsilon_M \equiv |\epsilon_M| e^{i\varphi_{SW}} \quad \tan \varphi_{SW} = \frac{2(m_L - m_S)}{\Gamma_S - \Gamma_L}. \quad (7)$$

Thus unitarity predicts the phase of mass CP violation in terms of Δm [1, 19]

$$\varphi_{SW} = (43.46 \pm 0.05)^\circ \quad (8)$$

~~CPT~~ in semileptonic decays

We will discuss the semileptonic decays of neutral kaons without assuming the $\Delta S = \Delta Q$ rule and the CPT symmetry [2, 4, 18].

The $\Delta S = \Delta Q$ rule is well supported by experimental data and is naturally accounted for by the Standard Model, where the $\Delta S = -\Delta Q$ transitions are possible only with two effective weak vertices. Explicit calculations in the SM give a suppression factor of about 10^{-6} – 10^{-7} [20]. Furthermore in any quark model, $\Delta S = -\Delta Q$ transitions can be induced only by operators with dimension higher than 6 and therefore should be suppressed [2, 21]. However large violation of the $\Delta S = \Delta Q$ rule does not conflict with any general principle. We can write [2, 4]

$$\begin{aligned} A(K^0 \rightarrow l^+ \nu \pi^-) &= a + b \\ A(K^0 \rightarrow l^- \nu \pi^+) &= c + d \\ A(\bar{K}^0 \rightarrow l^- \nu \pi^+) &= a^* - b^* \\ A(\bar{K}^0 \rightarrow l^+ \nu \pi^-) &= c^* - d^* \end{aligned}$$

CPT implies $b = d = 0$, CP implies $\Im(a) = \Im(c) = \Re(b) = \Re(d) = 0$, T requires real amplitudes and $\Delta S = \Delta Q$ implies $c = d = 0$. Then

$$\delta_{S,L} = \frac{\Gamma_{S,L}^{l^+} - \Gamma_{S,L}^{l^-}}{\Gamma_{S,L}^{l^+} + \Gamma_{S,L}^{l^-}} = 2\Re(\epsilon_{S,L}) + 2\Re\left(\frac{b}{a}\right) \mp 2\Re\left(\frac{d^*}{a}\right)$$

$$\delta_S - \delta_L \propto \Re\Delta, \Re d^* \quad (9)$$

Thus a non-vanishing value of the difference $\delta_S - \delta_L$ would be an evidence of CPT violation, either in the mass matrix or in the $\Delta S = -\Delta Q$ amplitudes (Δ and d^*/a cannot be disentangled by semileptonic decays alone). The sum $\delta_S + \delta_L$ has CPT-conserving ($\Re(\epsilon_M)$) and CPT-violating ($\Re(b/a)$) contributions that cannot be disentangled.

~~CPT~~ in $K \rightarrow \pi\pi$

CPT can be violated in the mass according to eq.(6) and in the amplitudes. If CPT is not conserved in $K \rightarrow \pi\pi$ the new amplitudes B_I 's appear:

$$\begin{aligned} A(K^0 \rightarrow \pi\pi(I)) &\equiv (A_I + B_I) e^{i\delta_I} \\ A(\bar{K}^0 \rightarrow \pi\pi(I)) &\equiv (A_I^* - B_I^*) e^{i\delta_I} \end{aligned}$$

Defining as usual

$$\eta_{+-} = \frac{A(K_L \rightarrow \pi^+ \pi^-)}{A(K_S \rightarrow \pi^+ \pi^-)} \quad \eta_{00} = \frac{A(K_L \rightarrow \pi^0 \pi^0)}{A(K_S \rightarrow \pi^0 \pi^0)}$$

and noticing that (8) is approximately equal, in the CPT limit, to the phase of ϵ' , then the η 's phases must be equal in the CPT limit. In fact the following CPT bound has been established experimentally [1, 18, 19, 22]

$$\phi_{+-} - \phi_{00} = 0.22 \pm 0.45$$

BELL-STEINBERGER RELATION AND CPT

If we think that the probability conservation is valid up to shorter distances than CPT then even if CPT is violated we can impose tht unitarity must be valid [2, 3, 23]. Then if we consider the time evolution of an initial kaon state which is a a quantum superposition of K_S, K_L :

$$|K(t)\rangle = a_S|K_S\rangle + a_L|K_L\rangle \quad (10)$$

and we impose probability conservation, for any a_S, a_L , as

$$-\frac{d}{dt}|\langle K(0)|K(0)\rangle|^2 = \sum_f |a_S A(K_S \rightarrow f) + a_L A(K_L \rightarrow f)|^2.$$

This turns in a relation among $K_{S,L}$ masses and widths defined in (6),(7) and all $K_{S,L}$ branching ratios:

$$\Rightarrow (1 + i \tan \varphi_{SW}) [\Re(\epsilon_M) - i \Im(\Delta)] = \sum_f \alpha_f \quad (11)$$

where we have encoded in α_f 's all the $K_{S,L}$ branching ratios, $B_f^{S,L}$:

$$\alpha_f = B_{+-}^S \eta_{+-}, B_{00}^S \eta_{00}, B_{+-\gamma}^S \eta_{+-\gamma}, \frac{\tau_L}{\tau_S} B_{000}^L \eta_{000}, \dots$$

Now an accurate experimental knowledge of the various $\varphi_{SW}, \epsilon_M, \alpha_f$'s ($\alpha_{\pi\pi}, \alpha_{\pi\pi\gamma}, \alpha_{000}, \dots$) determines a limit on $\Im(\Delta)$ in eqs.(6) and (11). The largest experimental error is now coming from α_{000} (SM prediction $1.9 \cdot 10^{-9}$); the published result of CPLEAR [24], $B_{000}^S < 1.4 \cdot 10^{-5}$, and the interesting preliminary limit of NA48/1 [25] with $B_{000}^S < 3 \cdot 10^{-7}$ (90%CL) lead respectively to [26], [25]

- CPLEAR $\Rightarrow \Im(\Delta) = (2.4 \pm 5.0) \times 10^{-5}$
- NA48/1 $\Rightarrow \Im(\Delta) = (-1.2 \pm 3.0) \times 10^{-5}$

The KLOE results in this channel are very promising [27] $B_{000}^S < 2.1 \cdot 10^{-7}$, and would improve the NA48/1 results.

Now we can use these results in eq.(6): this CPT limits are WORST than the neutrino limits in eq.(4). To improve we need a more accurate determination of B_{+-}^S, B_{00}^S , obtainable at future DAΦNE [21, 28].

CP ASYMMETRIES IN $K^+ \rightarrow 3\pi$ AND FINAL STATE INTERACTION

Direct CP violation in charged kaons is subject of extensive researches at NA48/2 [29]. Studying the $K \rightarrow 3\pi$ Dalitz distribution in Y, X [1, 30, 31]

$$|A(K \rightarrow 3\pi)|^2 \sim 1 + g Y + j X + \mathcal{O}(X^2, Y^2) \quad (12)$$

and determining both charged kaon slopes, g_{\pm} , we can define the slope charge asymmetry:

$$\Delta g/2g = (g_+ - g_-)/(g_+ + g_-). \quad (13)$$

Final State
Interaction

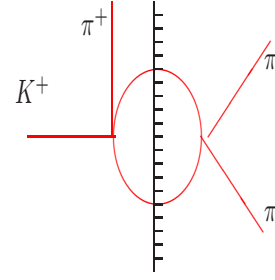


Figure 1: Final state interaction in $K \rightarrow 3\pi$: absorptive contribution.

There are two independent $I = 1$ isospin amplitudes (a, b),

$$A(K^+ \rightarrow \pi^+ \pi^+ \pi^-) = a e^{i\alpha_0} + b e^{i\beta_0} Y + \mathcal{O}(Y^2, X^2) \quad (14)$$

with corresponding final state interaction phases, α_0 and β_0 . The hope is that Δg in (13) does **NOT** need to be suppressed by a $\Delta I = 3/2$ transition. The strong phases, generated by the $2 \rightarrow 2$ rescattering in Fig. (1), are approximated here by their value at the center of the Dalitz plot, but actually have their own kinematical dependence [32] and can be expressed in terms of the Weinberg scattering lengths, a_0 and a_2 . It is particularly interesting to try to write down a Standard Model (SM) theoretical expression for $\Delta g/2g$, valid if there is a good chiral expansion for the CP conserving/violating a, b amplitudes [31, 33]. In fact under this assumption we neglect, the $\mathcal{O}(p^6)$ amplitudes $a^{(6)}, b^{(6)}$ and write [31, 33]

$$\begin{aligned} \frac{\Delta g}{2g} &= \frac{\Im A^0}{\Re A^0} (\alpha_0 - \beta_0) \left(\frac{\Re b^{(4)}}{\Re b^{(2)}} - \frac{\Im b^{(4)}}{\Im b^{(2)}} + \frac{\Im a^{(4)}}{\Im a^{(2)}} - \frac{\Re a^{(4)}}{\Re a^{(2)}} \right) \\ &\sim 22\epsilon' (\alpha_0 - \beta_0) \sim 10^{-5}. \end{aligned}$$

This result can be improved by accounting for the kinematical dependence of the strong phases [32]; here we have approximated the strong phase difference, $(\alpha_0 - \beta_0) \sim 0.1$ [34], by its value at the center of the Dalitz plot. More accuracy to determine (14) can be obtained by evaluating the $\mathcal{O}(p^6)$ [35]. Also a direct determination of the strong phases, which is possible through time interferences, as we shall see later, would be very welcome. Recently, a new strategy has been suggested: NA48/2 at CERN [36] has accumulated a lot of charged kaons, in particular $K^+ \rightarrow \pi^+ \pi^0 \pi^0$, also with an accurate scan in the $\pi^0 \pi^0$ -invariant mass distribution, $M_{\pi^0 \pi^0}$, finding a cusp at $M_{\pi^0 \pi^0} = M_{\pi^+ \pi^-}$. This result has been nicely investigated by Cabibbo [37], which explains the ‘‘cusp’’ as an effect due to the opening of the $\pi^+ \pi^-$ -threshold in Fig. (1). Since the rescattering $\pi^+ \pi^- \rightarrow \pi^0 \pi^0$ is proportional to $a_0 - a_2$ then

$$\left. \frac{d\Gamma(K^+ \rightarrow \pi^+ \pi^0 \pi^0)}{dM_{\pi^0 \pi^0}} \right|_{\text{NA48}} \Rightarrow \text{cusp for } M_{\pi^0 \pi^0} = M_{\pi^+ \pi^-} \Rightarrow^{\text{cusp}} a_0 - a_2.$$

This should give this strong phase difference to a very good accuracy [37] once isospin breaking effects are completely under control [38]. This is particularly exciting due the intense experimental (DIRAC) and theoretical efforts to determine $a_0 - a_2$.

TIME INTERFERENCES

One of major advantages at Φ -factories is the known initial $K_S K_L$ quantum state, fixed by the Φ quantum numbers. By choosing appropriate final states, f_1, f_2 , one can study several observables like $\Im(\epsilon'/\epsilon)$ [4]. This has proven to be very difficult so far [21] but there are other interesting possibilities.

$K \rightarrow 3\pi$ and advantages of KLOE/CPLEAR

Even in the CP limit K_S can decay in 3π if 3π are in high angular momentum (and $I = 2$) state

$$A(K_S \rightarrow \pi^0 \pi^+ \pi^-) = \gamma X(1 + i\delta_2) - \xi XY,$$

γ and ξ are $\Delta I = 3/2$ transitions while δ_2 is the final state interaction phase. γ is predicted by isospin while ξ [39] and δ_2 by ChPT [34]. Since δ_2 is very small (~ 0.1), the branching $Br(K_S \rightarrow \pi^0 \pi^+ \pi^-)$, is not very sensitive to δ_2 .

At Φ -factory, choosing as final states, $f = \pi^+ \pi^- \pi^0, l\pi\nu$, and by opportune kinematical cuts [40] it is possible to find a time dependent asymmetry proportional to

$$\int_+ \Re(A_L^{+-0} A_S^{+-0*}) [\cos(\Delta mt) + \tilde{\delta} \sin(\Delta mt)] d\phi_{3\pi}, \quad (15)$$

where

$$\tilde{\delta} \simeq \alpha_0 - \delta_2 \quad (16)$$

By opportune time dependent studies it is possible to measure this observable linear in A_S^{+-0} and in the final state phase. Another interesting channel is $K_L \rightarrow \pi^+ \pi^- \gamma$, where it is possible to extract, with a high statistics Φ -factory, the direct CP violation component [4, 41, 42]. Time interferences in $K_L \rightarrow \pi^+ \pi^- e^+ e^-$ may also be interesting [43].

CONCLUSIONS

At interferometry machines, like Φ -factories, with high statistics, let us say 10^{12} kaons, the golden searches are $\Im(\epsilon'/\epsilon)$, the semileptonic modes and η_{000} and η_{+-0} [4]. But we think that also the CP conserving $A(K_S \rightarrow \pi^+ \pi^- \pi^0)_{CP=+}$ and final state interactions in $K \rightarrow 3\pi$ will be very useful. Particularly after the good news from NA48/2 and Cabibbo [37]. The charge asymmetry limits in $K^\pm \rightarrow 3\pi$ and $K^\pm \rightarrow \pi\pi\gamma$ [44] are going also to be improved and may be tested to an interesting level. CPT tests are also a clear target: to this purpose let's stress again that we need improvement in $K \rightarrow 2\pi$ amplitudes. With larger statistics, of course, more is possible, like for instance the interesting time dependent studies in $K_L \rightarrow \pi^0 e^+ e^-$ [45]. The rare kaon decays program is also very rich [46].

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